

Anomalous $HZ\gamma$ couplings in photon-induced collisions at the LHC

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Abstract

We have examined $HZ\gamma$ vertex to obtain the limits on anomalous a_γ , b_γ and \tilde{b}_γ couplings in a model independent way through the γp collisions via the process $pp \rightarrow p\gamma p \rightarrow p H q X$. The sensitivities to the anomalous couplings can be obtained as $|b_\gamma|$, $|\tilde{b}_\gamma| \sim 10^{-3}$ for the integrated luminosity of $L_{int} = 100 \text{ fb}^{-1}$ at the LHC with $\sqrt{s} = 14 \text{ TeV}$.

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I. INTRODUCTION

After the discovery of Higgs boson by the ATLAS and CMS Collaborations at the LHC [1, 2], properties of Higgs boson have been studied extensively. Higgs boson couplings to the Standard Model (SM) particles are important because these couplings may give some hints for physics beyond the SM. Tree-level neutral bosons coupling for $HZ\gamma$ vanish within the electroweak interactions. Therefore, any detected signals of these tree-level couplings would indicate the existence of new physics. In a common scenario beyond the SM, the corrections from higher dimensional operators can be calculated through an effective Lagrangian. Being consistent with Lorentz and gauge invariance, the general structure for $HZ\gamma$ vertex can be written as [3, 4],

$$\Gamma_{\mu\nu}^{\gamma} = g_Z M_Z \left[a_{\gamma} g_{\mu\nu} + \frac{b_{\gamma}}{M_Z^2} (q_{1\nu} q_{2\mu} - g_{\mu\nu} q_1 \cdot q_2) + \frac{\tilde{b}_{\gamma}}{M_Z^2} \epsilon_{\mu\nu\alpha\beta} q_1^{\alpha} q_2^{\beta} \right], \quad (1)$$

where q_1 and q_2 represent momentum of photon and Z boson, respectively. M_Z is the mass of Z boson; $g_Z = e/\cos\theta_W \sin\theta_W$; a_{γ} , b_{γ} and \tilde{b}_{γ} are constants which can be written in form factors. Here, a_{γ} vanishes according to the electromagnetic gauge invariance for $q_1^2 = 0$.

In the photon-induced processes a quasi-real photon emitted from one of the proton beam [5, 6] can be described in the framework of equivalent photon approximation (EPA). For a process in a photon induced γp collision can be different from pure deep inelastic scattering process by means of two experimental signatures emerge in the following way [7–9]: First, forward detectors can detect the particles with large pseudorapidity. If the proton emits a photon, it scatters with a large pseudorapidity and can not be detected from the central detectors. However, potential forward detectors located at 220 m and 420 m away from the interaction point can detect the particles with large pseudorapidity providing some information on the scattered proton energy. Second, if the photon emitting intact protons exits the central detector without being detected, the energy deposit in the forward region decreases compared to the case in which the proton remnant is detected by the calorimeters. Accordingly, one of the forward regions of the central detector has a large energy deficiency. The region devoid of particles defines forward rapidity gaps. pp backgrounds from deep inelastic processes can be separated by applying a selection cut on this quantity.

Photon induced processes at the LHC have been studied as a probe of new physics beyond the SM [10–18]. Extensive studies on determining the sensitivity to the $HZ\gamma$ vertex have

been performed at $e\gamma$ [19, 20], e^-e^+ [3, 21–24] and pp [25] collisions.

In this work, we have studied anomalous $HZ\gamma$ vertex to obtain the limits on a_γ , b_γ and \tilde{b}_γ couplings in a model independent way through a γp collision via the process $pp \rightarrow p\gamma p \rightarrow pHqX$ at the LHC. For all calculations, we use the computer package CalcHEP [26] by implementing the anomalous interaction vertices given in Eq. 1.

We consider the acceptance regions of the ATLAS and CMS forward detectors to tag the protons with some energy loss fraction $\xi = E_{\text{loss}}/E_{\text{beam}}$. ATLAS and CMS experiments will have forward detectors with the acceptance of $0.0015 < \xi < 0.15$ [8, 9] within the pseudorapidity ranges $9.5 < \eta < 13$. When the forward detectors are installed closer to the interaction points, higher ξ value is obtained. Therefore, we define the parameter sets corresponding to these acceptances and pseudorapidity ranges. The parameters can also be related to the transverse momentum cuts on the tag protons as,

$$p_T = \frac{\sqrt{E_p^2(1-\xi)^2 - m_p^2}}{\cosh \eta} \quad (2)$$

where E_p and m_p are the energy and mass of proton, respectively. We define the parameter sets, namely PI, PII and PIII within the pseudorapidity range $9.5 < \eta < 13$ for minimal transverse momentum cuts on the scattered protons with $p_T > 0.03$ GeV, $p_T > 0.1$ GeV and $p_T > 0.2$ GeV, respectively.

II. DECAY WIDTH FOR $HZ\gamma$

The decay width of $H \rightarrow Z\gamma$ with anomalous couplings can be calculated considering the effective vertex in Eq. 1 as,

$$\Gamma(H \rightarrow Z\gamma) = \frac{\alpha M_Z^2 (M_H^2 - M_Z^2)}{8c_W^2 s_W^2 M_H^3 M_Z^4} \left[8a_\gamma^2 M_Z^4 + 6a_\gamma b_\gamma M_Z^2 (M_Z^2 - M_H^2) + (b_\gamma^2 + \tilde{b}_\gamma^2) (M_H^2 - M_Z^2)^2 \right] \quad (3)$$

where $s_W \equiv \sin \theta_W$ and $c_W \equiv \cos \theta_W$, M_H denotes mass of the Higgs boson. There is also contribution from one loop diagram including $HZ\gamma$ anomalous couplings. However, this contribution is proportional to the power of six of the anomalous couplings. Taking into account the experimental bounds on these couplings, which are smaller than 10^{-2} , tree level contribution dominates.

The decay width of $H \rightarrow Z\gamma$ depending on the anomalous couplings is given in Fig. 1. In Fig. 1, we set two of these anomalous couplings equal to zero while varying the other

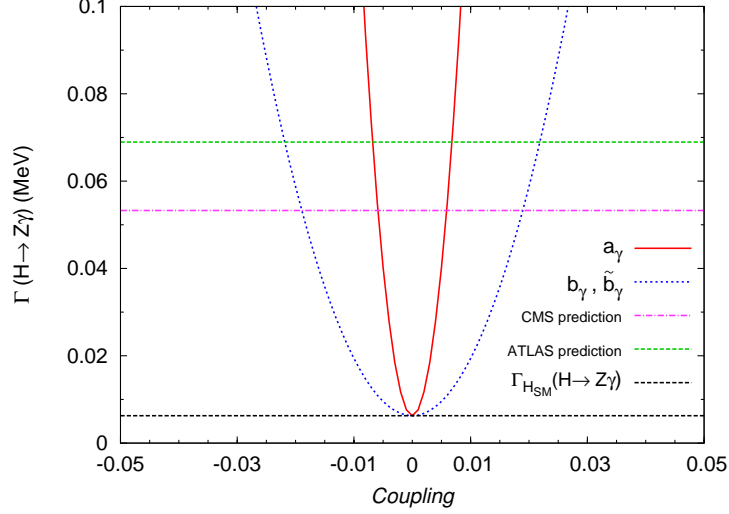


FIG. 1: Decay width for $H \rightarrow Z\gamma$ depending on the anomalous couplings a_γ , b_γ , \tilde{b}_γ .

coupling changes in the range $[-0.05, 0.05]$. The horizontal dashed line (black) denotes the one loop calculation of the decay width $H \rightarrow Z\gamma$, which is 6.27×10^{-3} MeV [27] for the Higgs boson mass of 125 GeV within the framework of the SM. The limits on the anomalous couplings can be extracted from the intersection points of the experimental predictions and the calculated values of decay width $H \rightarrow Z\gamma$. It is seen from Fig. 1 that the prediction from ATLAS [1] experiment limits these anomalous couplings as $|a_\gamma| < 0.007$ and $|b_\gamma|, |\tilde{b}_\gamma| < 0.022$. The CMS [2] prediction leads to more strict bounds. Due to more restriction on anomalous coupling a_γ we assume $a_\gamma = 0$, while other couplings allowed to changed in the considered range.

III. CROSS SECTION FOR SINGLE HIGGS PRODUCTION

The contributing tree level Feynman diagrams for the single production of Higgs boson through $\gamma q \rightarrow Hq$ subprocess (where $q = u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}$) are shown in Fig. 2. The differential cross section for the subprocess $\gamma q \rightarrow Hq$ is obtained as neglecting quark masses,

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi^2 \alpha^2 (12s_W^2 - 8s_W^4 - 9)\hat{t}}{18c_W^4 s_W^4 M_Z^2 [(\hat{t} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} [4a_\gamma^2 M_Z^4 + 4a_\gamma b_\gamma M_Z^2 (\hat{t} - M_H^2) + (b_\gamma^2 + \tilde{b}_\gamma^2) [M_H^4 + \hat{t}^2 + 2(\hat{s} - 2M_H^2)(\hat{s} + \hat{t})]]. \quad (4)$$

We find the total cross section of $pp \rightarrow p\gamma p \rightarrow pHqX$ process by integrating differential cross section of $\gamma q \rightarrow Hq$ subprocess over the parton distribution functions CTEQ6L [28]

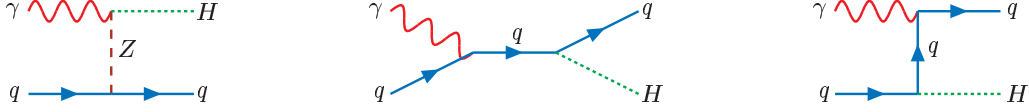


FIG. 2: Feynman diagrams for the subprocess $\gamma q \rightarrow Hq$.

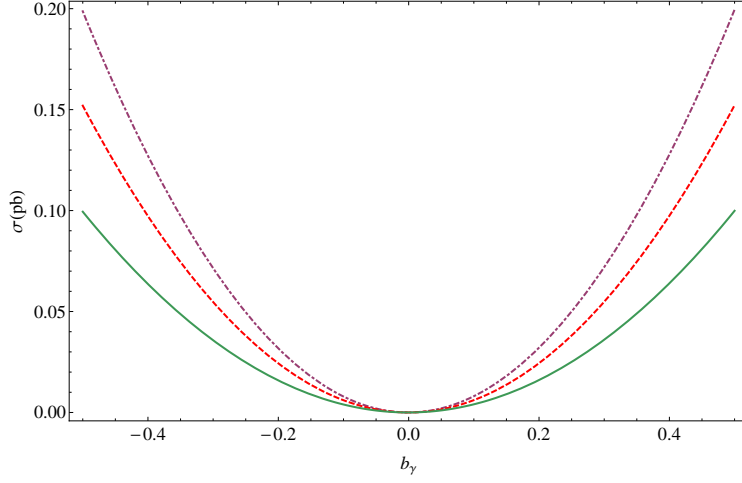


FIG. 3: The total cross section depending on anomalous coupling b_γ with $\sqrt{s} = 14$ TeV. Dot-dashed, dashed and solid lines correspond to parameter sets PI, PII and PIII, respectively.

and photon spectrum in EPA [5–7], by using the CalcHEP.

In Figs. 3 and 4 the total cross sections of $pp \rightarrow p\gamma p \rightarrow pHqX$ process as a function of b_γ and \tilde{b}_γ are illustrated for the parameter sets PI, PII, PIII.

IV. SENSITIVITY TO ANOMALOUS COUPLINGS

The χ^2 test for the bounds of anomalous b_γ and \tilde{b}_γ couplings at 95 % C.L. can be written as

$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma_{AN}}{\sigma_{SM} \delta} \right)^2 \quad (5)$$

where σ_{AN} is the cross section including considered anomalous couplings; $\delta = \frac{1}{\sqrt{N}}$ is the statistical error and here N is the number of SM events. The number of events are given by $N = \sigma_{SM} \times L_{int} \times BR(H \rightarrow b\bar{b}) \times (\epsilon_{b-tag})^2$ where ϵ_{b-tag} denotes the b -tagging efficiency and L_{int} is the integrated luminosity. We use kinematical cuts for transverse momentum of final state quarks to be $p_T^j > 15$ GeV and pseudorapidity to be $|\eta^j| < 2.5$.

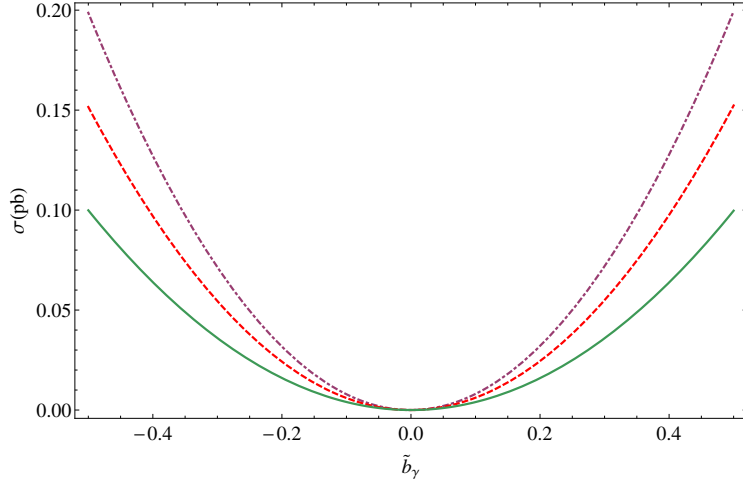


FIG. 4: The total cross section depending on anomalous coupling \tilde{b}_γ with $\sqrt{s} = 14$ TeV. Dot-dashed, dashed and solid lines correspond to parameter sets PI, PII and PIII, respectively.

TABLE I: Sensitivity (95% C.L.) to anomalous $HZ\gamma$ couplings for parameter set PI in the γp collisions at the LHC with $\sqrt{s} = 14$ TeV for various integrated luminosities.

$L(\text{fb}^{-1})$	b_γ	\tilde{b}_γ
50	$(-9.93 \times 10^{-3}, 8.89 \times 10^{-3})$	$(-9.92 \times 10^{-3}, 8.90 \times 10^{-3})$
100	$(-8.44 \times 10^{-3}, 7.39 \times 10^{-3})$	$(-8.42 \times 10^{-3}, 7.41 \times 10^{-3})$
200	$(-7.19 \times 10^{-3}, 6.14 \times 10^{-3})$	$(-7.17 \times 10^{-3}, 6.16 \times 10^{-3})$

In Tables I, II and III, we have listed 95% C.L. sensitivity limits on the couplings b_γ and \tilde{b}_γ for various integrated luminosities by varying one coupling at a time, for sets of minimal transverse momentum cuts PI, PII and PIII, respectively.

The sensitivities to the anomalous couplings in $b_\gamma - \tilde{b}_\gamma$ plane are plotted when two of the anomalous parameters are changed independently in Figs. 5, 6 and 7 for the parameter sets PI, PII and PIII, respectively.

V. CONCLUSIONS

We have analyzed the single production of Higgs boson including anomalous $HZ\gamma$ vertices at the photon-induced γp collisions at the LHC. This process gives opportunity to investigate anomalous $HZ\gamma$ couplings $|b_\gamma|$ and $|\tilde{b}_\gamma|$ at the order of 10^{-3} . We find the best limits on

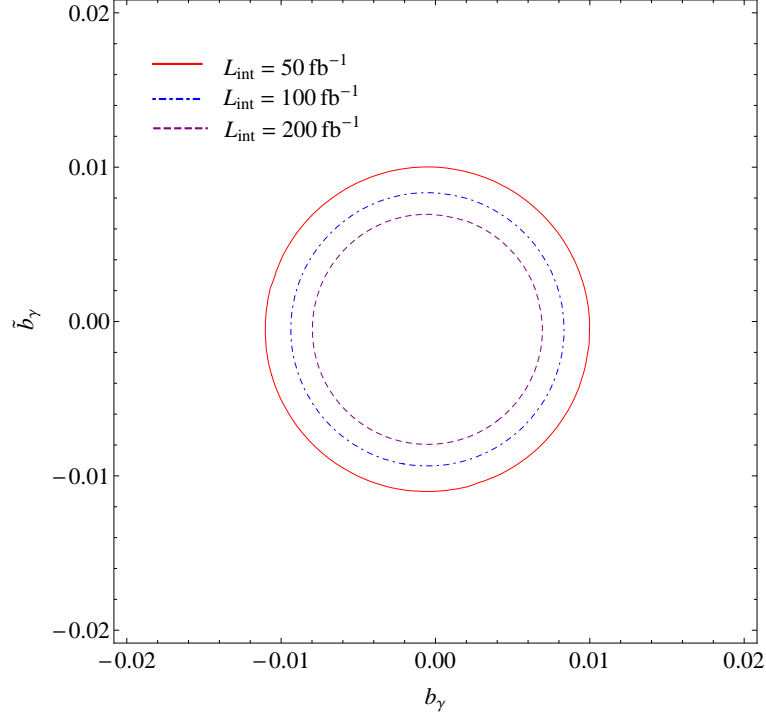


FIG. 5: Two dimensional contour plot for anomalous couplings b_γ and \tilde{b}_γ for the process $\gamma q \rightarrow Hq$ with $\sqrt{s} = 14$ TeV for parameter set PI.

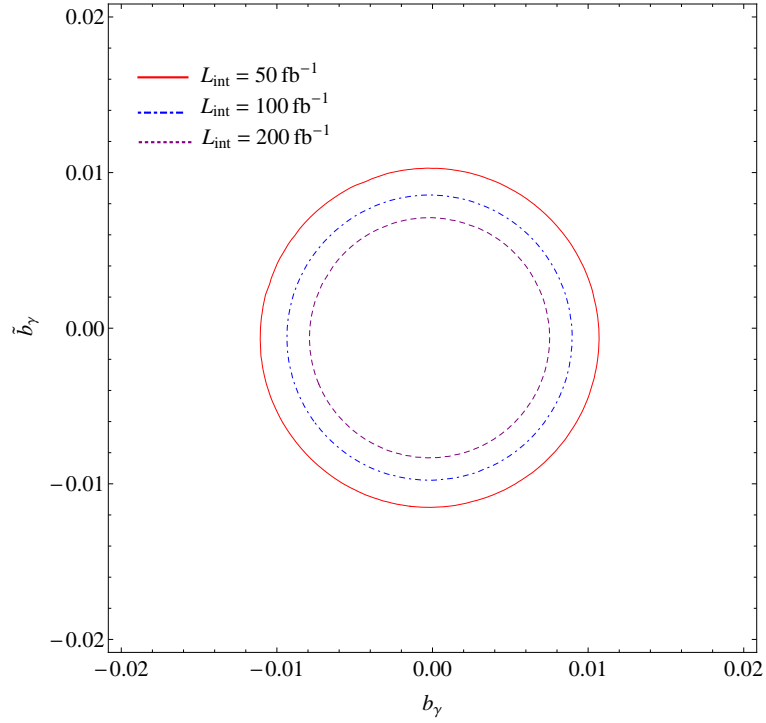


FIG. 6: Two dimensional contour plot for anomalous couplings b_γ and \tilde{b}_γ for the process $\gamma q \rightarrow Hq$ with $\sqrt{s} = 14$ TeV for parameter set PII.

TABLE II: Same as Table I, but for parameter set PII.

$L(\text{fb}^{-1})$	b_γ	\tilde{b}_γ
50	$(-9.89 \times 10^{-3}, 9.51 \times 10^{-3})$	$(-1.03 \times 10^{-2}, 9.11 \times 10^{-3})$
100	$(-8.35 \times 10^{-3}, 7.96 \times 10^{-3})$	$(-8.79 \times 10^{-3}, 7.57 \times 10^{-3})$
200	$(-7.05 \times 10^{-3}, 6.67 \times 10^{-3})$	$(-7.50 \times 10^{-3}, 6.27 \times 10^{-3})$

TABLE III: Same as Table I, but for parameter set PIII.

$L(\text{fb}^{-1})$	b_γ	\tilde{b}_γ
50	$(-1.11 \times 10^{-2}, 9.96 \times 10^{-3})$	$(-1.03 \times 10^{-2}, 1.07 \times 10^{-2})$
100	$(-9.43 \times 10^{-3}, 8.29 \times 10^{-3})$	$(-8.61 \times 10^{-3}, 9.07 \times 10^{-3})$
200	$(-8.03 \times 10^{-3}, 6.88 \times 10^{-3})$	$(-7.20 \times 10^{-3}, 7.67 \times 10^{-3})$

these anomalous couplings which can be compared to the bounds $O(10^{-2})$ obtained from the associate production of HZ [23] at linear collider with $\sqrt{s} = 500$ GeV.

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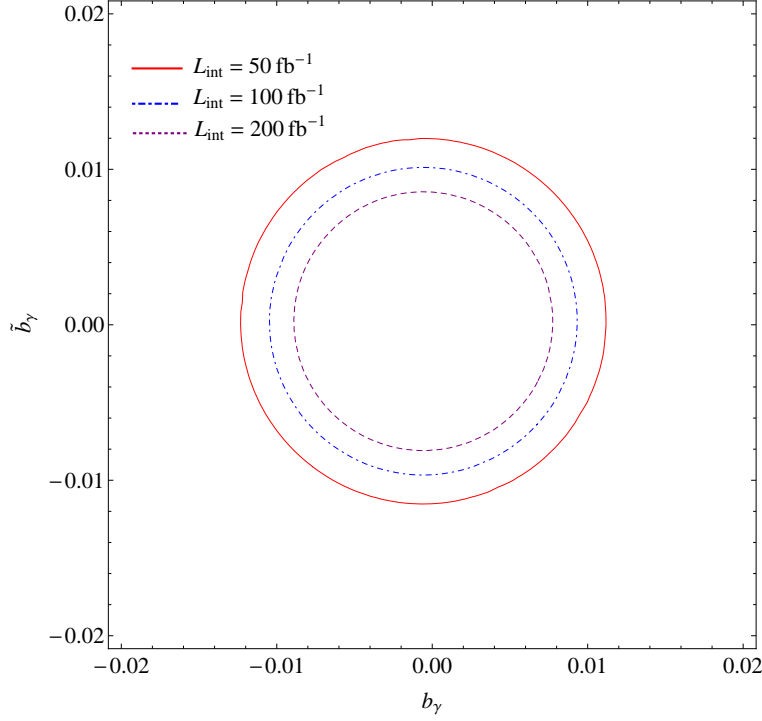


FIG. 7: Two dimensional contour plot for anomalous couplings b_γ and \tilde{b}_γ for the process $\gamma q \rightarrow Hq$ with $\sqrt{s} = 14$ TeV for parameter set PIII.

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